A Direct Translation Reading Aid for the Blind

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Abstract—**A reading device for the blind is proposed in which a facsimile of ordinary printed material is presented tactually. The tactile image is presented by a dense array of pins which can be made to vibrate individually through perforations in a plate on which the user's finger is rested.**

In the arrangement proposed, the image of ordinary printed matter is focused on an array of photocells which are coupled one-to-one to piezoelectric reeds which drive the image-producing pins. The feasibility of this arrangement has been evaluated, and relations among the design parameters are derived. The power required to drive each pin for adequate tactile stimulation is shown to be only about 30 μW. Present photocell sensitivities and integrated circuit techniques appear to be adequate for a convenient microminiature realization of this arrangement, although several technical development problems remain to be solved.

Successful reading tests with blind subjects are reported in which a computer controller simulates the optical portion of the system. The tactile images presented on a field of 96 piezoelectrically driven pins have been readable by the three subjects tested at rates of about 30 correct words per minute.

I. Introduction

ACCESS to the printed page has remained a major problem of the blind in spite of many attempts at a solution. Reviews of past developments toward this problem have been written by Farrell [1], Cooper [2], Freiberger and Murphy [3], Switzer and Bledsoe [4], Nye [5], and Shrager and Süsskind [6]. However, the major reading techniques employed by the blind are still the sighted reader, Talking Book, and Braille. While extremely useful, these techniques have obvious limitations in terms of independence afforded the reader and accessibility to an ever increasing range of printed documents.

The aim of the device proposed here is to make the printed material of the seeing *directly* usable by the blind. The conceptual arrangement of this reading aid is shown, in its simplest form, in Fig. 1. The printed material to be read, represented by the lower plane, is imaged on an array of photocells, represented by the middle plane. Each photocell controls a corresponding tactile stimulator-driver. A pin, connected to each stimulator-driver, can be made to vibrate through its hole in a perforated sensing plate, represented by the upper plane. Thus, as the user rests his finger on the sensing plate, he can sense a vibrating and grainy facsimile of the material being viewed.

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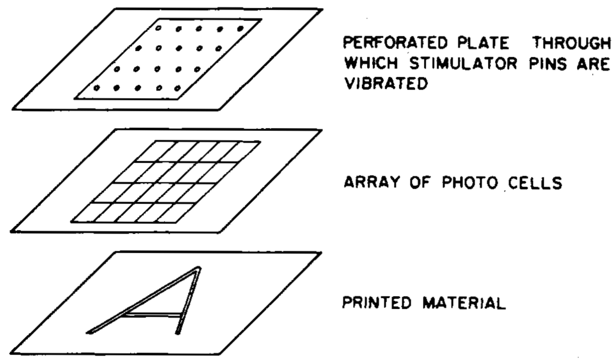


Fig. 1. Simplified concept of tactile direct translation reading aid.

Cooper, in his review of reading machines for the blind, suggests the classification "direct translation" be given devices of this type that perform a one-to-one transformation of an optical image to a corresponding tactile or auditory image. At the more complex end of this classification system is the "recognition" machine, which would identify each printed letter or word and present an output such as Braille, spelled speech, or spoken words. Two major advantages of the "direct translation" approach as a personal reading aid over the "recognition" approach are versatility and simplicity of implementation. Not only has the complexity and cost of "recognition" machines made them prohibitive for this application, but it is clear that their range of input material would always be more restricted than that of a "direct translation" device.

While the arrangement shown in Fig. 1 is not new, technological advances made in the last decade provide an attractive means to implement this concept. The authors anticipate that a small hand-held device which is simply rolled over the page being read is now within the range of possibility. A dense array of photocells can be coupled one-for-one with transistor switches in a microelectronic structure. These, in turn, can be connected one-for-one with piezoelectric bimorph reeds which can produce tactile stimulation. These connections can be arranged so that a darkened photocell gates the output of a small battery-powered oscillator to the corresponding reed. Thus the planar array of reed tips, some vibrating, some not, would generate a tactile image of the material being read. An integrated unit, with all parts automatically connected as a step in the fabrication, would be an ultimate answer for the construction of a useful device. Using these techniques, a reading aid, perhaps the size of a blackboard eraser, appears feasible in the present state of the art.

However, an attractive implementation would be useless if the output display is psychologically beyond human tactual sensing capabilities. In fact, some reports with embossed letters [7], [8] have indicated that tactile presentation of uncoded letter shapes permits only very slow reading. On the other hand, Farrell [1] has pointed out that from about 1818 to 1873 almost all English books for the blind were printed in embossed alphabetic shapes instead of Braille dots. These books were, of course, tactually readable with enough facility so as to be useful. Farrell attributes the abandonment of these embossed letters chiefly to the fact that Braille could also be written by the blind, whereas no satisfactory method of writing embossed letters then existed. Indeed, new results presented in this paper also suggest that alphabetic shapes are usefully readable tactually. Since this appears to be the case, the advantages of the "direct translation" approach over the "recognition" approach for a personal reading aid certainly warrant a re-examination of the "direct translation" approach in the light of our present knowledge and needs.

In examining the "direct translation" approach, both engineering and psychological factors must be considered. The first part of this paper identifies the requirements imposed on the photodetecting part of the reading aid and on the electromechanical stimulators. Properties of devices which appear attractive for the implementation of these functions are identified, and results of tests of these devices are discussed. The second part of the paper describes tactile reading tests performed with blind subjects. In these tests, a digital computer-controlled instrumentation system was used to simulate the optical portion of the reading aid and to present material to the subjects tactually in the form described above.

II. Photomechanical Design

The photomechanical design of the reading device is based, at the input end, upon the nature of the optical signals which are presented by ordinary reading matter to the reading device. At the output end, it must be based on the nature of the mechanical load of the finger which must be adequately stimulated to provide tactual perception of the shapes presented. We begin by evaluating, in an approximate way, the nature of the input signal, the mechanical load of the finger, and the amplitude of stimulation necessary to insure perception. Next we consider piezoelectric reeds which flex under application of voltage, indicating their properties as transducers and showing how they can be used as suitable tactile stimulators. The photoelectric detector and piezoelectric reed combination is designed from the data about the optical signals and the mechanical load requirements on the reed.

Optical Signals from Reading Matter

Illumination of the material being read will be provided by a small integral light source for uniformity and engineering simplicity. For reasons of economy in cost and weight, a moderate level of illumination should be chosen, for instance, that of a well-lighted reading room. A value of radiant power density which falls in the range of room lighting is 1 W/m^2. If this radiant power is concentrated at 0.54 micron, the wavelength of the eye's greatest sensitivity, it corresponds to a photon rate density of about 3×10^{18} photons/s/m^2. This density of photon flux can be taken as that coming from a sheet of white paper which is illuminated at a value within the typical range. The light reflected from the inked portions of printed material depends upon the nature of the surface and the ink. Typically, the light density coming from the inked portions of printed material is from 10 to 20 percent of the light from the white portions. The light signal which will fall on each photoconductor element depends upon the number of elements into which each character is divided. Typed characters are about 2 mm. high and the width of lines in the characters is typically $\frac{1}{5}$ mm. A conservative estimate of light from the separate elements is the radiant flux for a surface of 0.01 mm^2. This permits as many as 100 elements per letter and provides a margin for loss in transmission. Finally, the light signal for each element of the character can be estimated as 3×10^{10} photons per second. A change of signal to 10 or 20 percent of this value should switch on the vibrating reed controlled by the element.

The Mechanical Load of the Finger on the Stimulator

In experimental studies on vibrating reeds as tactile stimulators, Alonzo [9] and Hill [10] have measured the mechanical load which the surface of the finger presents to a vibrating pin touching it. In addition, Alonzo determined the smallest vibration which can be tactually detected for vibrating reeds. His results, which will be quoted below, approximately correspond to those reported by Sherrick [11] some years ago.

To characterize the mechanical load of the fingers simply is difficult since there are many variations in stimulators and their mode of operation. For example, the size of the simulator tip and the aperture can be varied. In the vibration of the tip, the motion may be essentially sinuosidal, with the stimulator in continuous contact with the skin, or contact may be intermittent. The mean position of the tip during vibration can be varied. In the reading tests described later, the perforated plate on which the fingers of the subject are placed can be changed in height and different subjects prefer different heights. The measurements quoted below on mechanical immittance come from tests in which the stimulator is always in contact with the skin. This case is chosen for simplicity in the belief that it provides specific data at least qualitatively significant for design in any mode of operation.

Alonzo determined for static deflection that the finger appears as a spring of stiffness 100 N/m to a 30-mil rod pressed axially against the fingertip. Hill measured the mechanical load of the finger under sinusoidal stimulation with a 30-mil pin moving through a 90-mil perforation in a plate on which the finger was placed. He measured both amplitude and phase of the motion. The force-to-displacement immittance varied from point to point on the finger and depended upon the subject; variation in a 4-to-1 range was typical. The phase angles of immittance were much less variable. Figure 2 shows a curve of typical values of force to displacement immittances taken from his data.

In the reading device, a sufficient amplitude of vibration of the stimulators must be maintained to provide detection. At the same time, to minimize the power requirement of the system, the smallest amplitude which provides adequate detection should be used. Alonzo determined the minimum amplitude of vibration which could be detected as a function of frequency. He found that an amplitude of about 6 microns at 60 c/s is clearly detectable and that the minimum amplitude of vibration which can be detected occurs at about 300 c/s. The earlier tests described by Sherrick employed a stimulator 146 mils in diameter and, at 40 c/s, the threshold amplitude of detection was about 4 microns while, at 200 to 400 c/s, the threshold decreased to less than 1 micron.

The selection of frequency and amplitude of vibration of the stimulators for the reading aid is not a critical choice. The power required, however, is an important factor in the choice. The average power required is found as follows:

Let

s be the displacement of the pin about its mean position,

f be the force of the pin on the finger,

and

Z_{fd} be the force-displacement immittance of the finger.

Then, for sinusoidal motion,

$$s = \mathrm{Re}\, Se^{j\omega t}, \qquad \dot{s} = \mathrm{Re}\, j\omega Se^{j\omega t}. \tag{1}$$

$$f = \mathrm{Re}\, Fe^{j\omega t}, \qquad F = SZ_{fd}. \tag{2}$$

The average power required to vibrate the pin on the finger is easily found to be

$$P_{\mathrm{av}} = \frac{|S|^2}{2}\omega\,|Z_{fd}|\,\sin\theta_{fd}. \tag{3}$$

To vibrate the pin at a peak amplitude of 10 microns at 50 c/s, which is considerably above the threshold of sensitivity, requires a power of 2.5 μW. To vibrate the pin at an amplitude of 2 microns at 200 c/s, also considerably above the threshold of sensitivity for that frequency, requires a power of 1 μW. In spite of the significant variations in both the mechanical impedance of the skin and of the differing threshold of detection, the power required to drive the stimulator does not seem to vary strongly with frequency.

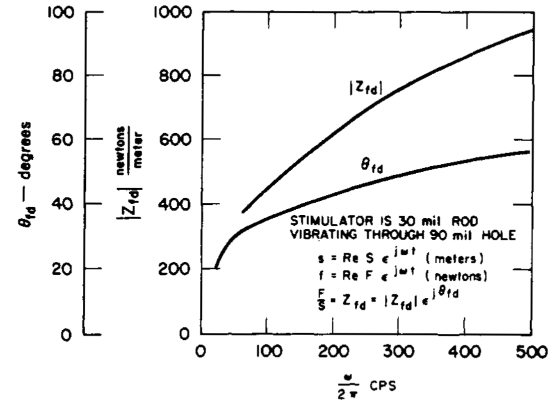


Fig. 2. Typical force-displacement immittance of finger to tactile stimulator.

The choice of a driving frequency for the stimulator is influenced by the anticipated reading rate and the requirement that each element of a letter provide at least a few cycles of vibration in every position as it moves by. To read 100 wpm tactually, allowing six spaces—five letters and a blank space—per word, and six elements per letter, one finds that 3600 elements must be scanned per minute, or 60 per second. For this reading rate, a vibration rate of 200 c/s will give just more than three cycles per element. Sixty cycles per second would permit only one cycle per element. Thus we conclude that a vibration rate of 200 to 300 c/s is desirable.

Design of the Piezoelectric Stimulators

To drive the vibrating pins which act as stimulators for the reading aid requires a form of motor which can be driven from the optoelectronic system. As indicated in the preceding section, the pins which act as stimulators are to be driven at approximately 200 c/s. The force-displacement immittance of the skin to the pins at 200 c/s is about 600 $e^{j(\pi/4)}$ N/m. The force-velocity immittance of the skin at 200 c/s is

$$\frac{600e^{j(\pi/4)}}{j2\pi[200]}$$

or 0.34 $[1-j]$ N/s/m. For suitable excitation, the pin should have an amplitude of 1 to 10 microns.

From (3), for a 10-micron deflection at 200 c/s, the average power required by the finger is

$$\frac{(10^{-5})^2(2\pi\, 200)}{2}(600)\sin\frac{\pi}{4} \text{ or } 27\ \mu\text{W}.$$

Piezoelectric reeds which flex under the application of voltage are suitable motors to drive the stimulator pins. A piezoelectric reed mounted in a cantilever manner is illustrated in Fig. 3. Such reeds, constructed of lead zirconate, are manufactured by the Clevite Corporation for use as generators in phonograph cartridges. In the reed illustrated in Fig. 3, the upper and lower surfaces are coated with silver, serving as the electrical ground terminal. The center conductor is a brass sheet. Under application of a voltage of proper polarity, the upper lead zirconate slab contracts longitudinally, the lower one extending. The result is that the reed flexes and the end deflects upward, s being positive. The opposite polarity of voltage has the opposite effect.

The behavior of the piezoelectric reed as a transducer is represented by the relationships which it provides between the electrical variables: charge, q, voltage, v, and the mechanical variables. The mechanical variables are the displacement of the tip upward, s, and the force impressed on the load by the reed, f. The applicable relationships are represented in terms of the sequence of models shown in Fig. 4. In Fig. 4(a), the electrical and mechanical ports are shown separately. The relationships between the variables are as follows [9], [12], [13]:

$$v = \frac{q}{C_e} + Nf \tag{4}$$

$$s = Nq - C_m f. \tag{5}$$

C_e is the electrical capacitance in farads, the mechanical port being unstressed.

C_m is the compliance of the mechanical port in meters per newton the electrical port being open-circuited.

N is the transfer constant, the unstressed displacement in meters per coulomb, or the open-circuit volts per newton.

In terms of (4) and (5), the electrical port and the mechanical port of the transducer may be shown in the manner of Fig. 4(b). The electrical port exhibits a capacitor in series with a voltage source v_m related to the mechanical port variable, force. The mechanical port exhibits a displacement generator s_e related to the electrical port variable, charge, and a series connection of a compliance.

The load on the mechanical port consists of the lumped mass at the end of the reed equivalent to its distributed mass along with the mechanical load represented by the finger tip. This is illustrated in Fig. 4(c).

The parameters of the transducer can be expressed in terms of the material properties of the lead zirconate and the dimensions of the cantilever. If we neglect the clamped portion of the cantilever, the following relationships can be shown to hold [9], [13]:

$$C_m = K_{cm}\frac{l^3}{wt^3}\ [\mathrm{m/N}] \quad M = K_m lwt\ [\mathrm{kg}]$$

$$C_e = K_{ce}\frac{lw}{t}\ [\mathrm{F}] \qquad N = K_n\frac{l}{wt}\ [\mathrm{V/N}]\ \text{or}\ [\mathrm{m/C}] \tag{6}$$

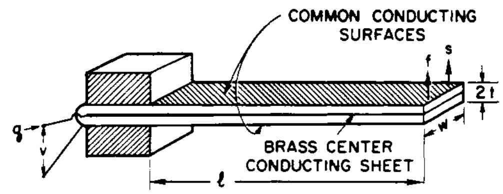


Fig. 3. Cantilever piezoelectric reed.

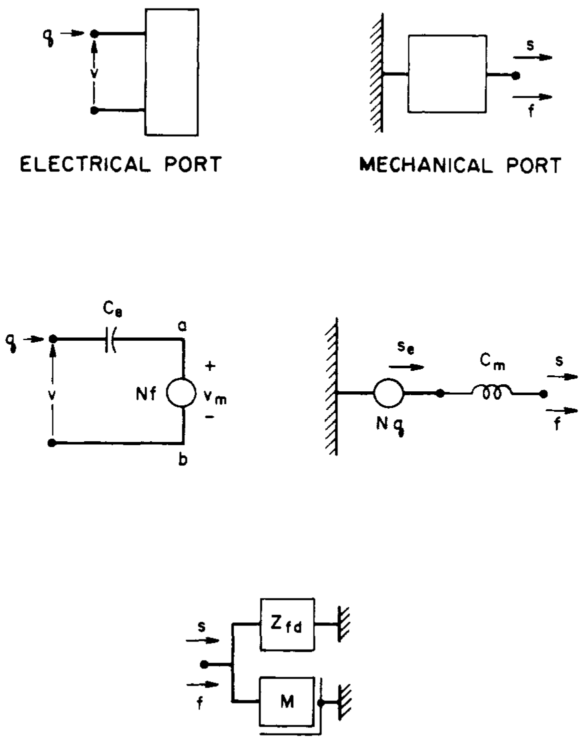


Fig. 4. Representations of the transducer and its load. (a) Model separating the ports. (b) Parameter representation of the transducer. (c) Mechanical load on mechanical port.

where M is the equivalent mass of the bimorph lumped at the top and the dimensions of the cantilever are given in inches. The constants used in (6) are found to be as follows for Clevite materials PZT-5B [9], [13]:

$$K_{ce} = 9.0 \times 10^{-10}, \qquad K_{cm} = 3.7 \times 10^{-10},$$
$$K_m = 4.9 \times 10^{-2}, \qquad K_n = 0.27. \tag{7}$$

To facilitate the design of the piezoelectric reed, a convenient step is to replace the voltage generator v_m in Fig. 4(b) with a passive circuit which bears a one-to-one correspondence to the mechanical circuit and draws precisely the same power, element for element. The identification of this analog proceeds by writing q in terms of v_m in the following steps. From this point, we consider exponentially varying values of the variables and focus attention on the complex voltages and currents of the form

$$v = \mathrm{Re}\ Ve^{j\omega t}, \tag{8}$$

in which the complex values are represented by capitals.

For the load on the mechanical port, Fig. 4(c), one writes

$$F = Z_{fd}S + [j\omega]^2MS = [Z_{fd} + (j\omega)^2M]S. \tag{9}$$

Solving (5), expressed in terms of the complex amplitudes, one has for Q

$$Q = \frac{S}{N} + \frac{C_mF}{N} \cdot \tag{10}$$

But, from Fig. 4(b) one observes that

$$F = \frac{V_m}{N} \cdot \tag{11}$$

Thus,

$$Q = \frac{S}{N} + \frac{C_m}{N^2} V_m. \tag{12}$$

One uses (9) to eliminate S from (12), writing

$$Q = \frac{F}{NZ_{fd} + [j\omega]^2M} + \frac{C_m}{N^2} V_m. \tag{13}$$

Employing (11), one finally gets

$$Q = \frac{V_m}{N^2Z_{fd} + [j\omega]^2MN^2} + \frac{C_m}{N^2} V_m. \tag{14}$$

Equation (14) can be readily rewritten

$$j\omega Q = I = \frac{V_m}{[N^2Z_{fd}/j\omega] + [j\omega]MN^2} + \frac{j\omega C_m}{N^2} V_m. \tag{15}$$

From (15), one recognizes the electric analog which presents precisely the same impedance from the points a–b of Fig. 4(b) as the electromechanical transducer and its load. The analog is shown in Fig. 5. The effect of the compliance of the reed is analogous to the effect of the capacitance C_m/N^2 farads; the mass of the reed behaves like an inductance of MN^2 henrys in series with the analog of the mechanical load of the finger. The analog of the load of the finger is an electrical impedance, $N^2Z_{fd}/j\omega$ ohms.

The design of the piezoelectric reed is the choice of l, w, and t such that a voltage v applied to the terminals delivers an average power of 27 μW to the load. For such an excitation and design the reed will be in vibration against the finger with a 10-micron amplitude at 200 c/s. In essence, the design of the stimulator is equivalent to selection of the parameters of the reactive components of Fig. 5, the selection being made in terms of l, w, and t, such that the source is most effectively coupled to the load.

The parameter values of the electrical elements of Fig. 5 can be expressed in terms of the dimensions and the constants of (6) and (7). The capacitance analog of the compliance C_m/N^2 is

$$C_m/N^2 = \frac{K_{cm}}{K_n^2} \frac{lw}{t} \quad \text{(farads)}. \tag{16}$$

Comparing (16) with (6), one comes to the interesting conclusion that, using (7),

$$C_m/N^2 = \frac{K_{cm}}{K_n^2K_{ce}} C_e = 5.6C_e. \tag{17}$$

The dimension-independent relationship between the two capacitances in Fig. 5 makes possible the simple equivalent of Fig. 6. Near the elements of Fig. 6 are shown the impedance values at 200 c/s. There is a wide range of values of the dimensions which will be workable. For the case in which the finger is not loading the reed, it will be in resonance when $6.6C_e$ is in resonance with MN^2 henrys. The losses in unloaded reeds, idealized to be zero in the models shown, are small, the quality factor Q being about 20 in the units tested. To avoid large amplitudes of vibration of the reeds not loaded by the skin, it is desirable that the frequency of operation be 10 percent away from the resonance frequency. The skin load exhibits a capacitive reactance, and one finds some advantage in the unloaded resonant frequency being below the frequency of the source.

Setting the unloaded resonance about 10 percent below the 200 c/s frequency of operation amounts to setting

$$[1.1]1.4 \times 10^5 \frac{t}{lw} = [0.9]4.5 \frac{l^3}{wt} \cdot \tag{18}$$

Consideration of (18) indicates that the resonance requirement is independent of w and requires that

$$\frac{l^4}{t^2} = 3.8 \times 10^4. \tag{19}$$

The minimum t is about 0.01 inch. Thus one finds that l is 1.4 inches. The choice of w is found by considering the Norton equivalent source looking back from points a–b of Fig. 6, yielding the circuit shown in Fig. 7. One wishes to provide the required 27 μW with a moderate value of source voltage. Consideration of the load resistance indicates that the maximum value of w should be employed. Since reeds must be placed in a dense array, we choose $\frac{1}{16}$ inch for w. On Fig. 7 are shown the values of the impedances for $l=1.4$ inches, $t=0.01$ inch, and $w=\frac{1}{16}$ inch. In order to obtain 27 μW to the finger, one finds that an rms voltage of 17 volts is required.

To construct a dense array of stimulators, each with a connected pin to be driven through a perforation in the sensing plate, a simple arrangement is to set the reeds at 45° to the sensing plate. The experimental array which was used for the tests described later in the paper is

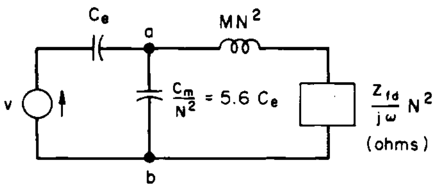
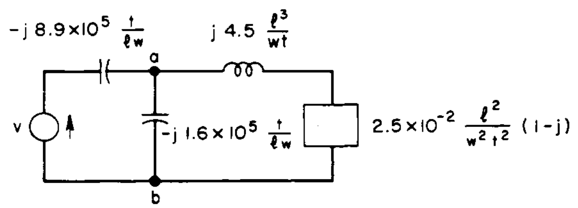


Fig. 5. The all-electric analog of the piezoelectric reed and its load.



NOTE:
THE EXPRESSIONS ADJACENT TO EACH CIRCUIT ELEMENT ARE THE 200 cps IMPEDANCES; ℓ, w, AND t ARE IN INCHES.

Fig. 6. The circuit of Fig. 5 with impedance values in terms of bimorph dimensions.

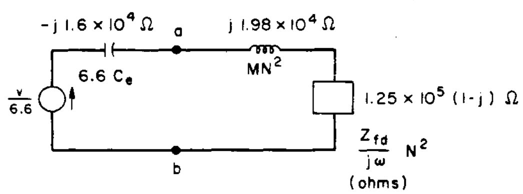


Fig. 7. The Norton equivalent of the source of Fig. 6 with the connected load.

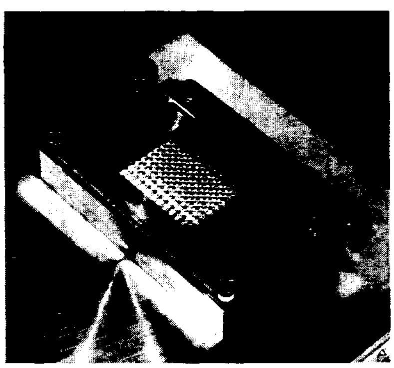


Fig. 8. A 12×8 array of piezoelectric bimorph tactile stimulators.

constructed in this manner. The 8×12 array of stimulators, as shown in the photograph of Fig. 8, is spaced at $\frac{1}{8}$-inch intervals.

Design of the Photoelectric Detectors

The function of the photoelectric detectors is to respond to the level of light signals described earlier, each cell gating power to the connected stimulator only when its element is dark. The lighted elements provide about 3×10^{10} photons per second, dark elements providing about $\frac{1}{5}$ to $\frac{1}{10}$ of that amount. The electrical load, to which a few tens of volts must be supplied with a power of a few tens of microwatts, is illustrated in Fig. 6. The load, for the dimensions indicated above, is a capacitive reactance of about 10^5 ohms coupling the reflected impedance of the skin, which has a somewhat higher magnitude. The interval within which the photodetector must operate is certainly no longer than the period of the source driving the stimulators; here 1/200 second is considered.

Two photodetectors controlling switches are shown in Fig. 9. In each, a photon flux from the element of the page being scanned, φ photons per second, controls the coupling of the source e_s to the bimorph. The photodetector in both cases is a photoconductor on which the flux φ falls. In Fig. 9(a), when the flux is at a low value, typical of that obtained when the element is a dark portion of a letter, the source is coupled to the bimorph, causing it to vibrate. When sufficient flux of photons falls on the photoconductor, its resistance is lowered, and the bimorph receives too little power to vibrate significantly. This form of circuit was employed by Alonzo [9]; under strong illumination, the photoconductor cells presented resistances of 30 000 ohms. In his circuit, the distribution resistors R are 5×10^5 ohms. Figure 10 is a photograph of the photoconductor array described by Alonzo. In it, 40 photocells are deposited on a $7/8 \times 9/8$-inch surface. The photoconductor terminals are interdigitated to reduce the separation between conductors.

The arrangement of Fig. 9(b) is similar except that the photoconductor controls a transistor, causing it to switch on or off, respectively, when the element is dark or light. The photoconductor-transistor circuit has higher sensitivity than the resistor-photoconductor circuit; moreover, it requires smaller power when the bimorphs are not vibrating.

Alternative possibilities to the photoconductors of Fig. 9 are *p-n* photodiodes or phototransistors. We will compare these alternatives to the photoconductor after showing the relationships between the design parameters of the photoconductor. Its dimensions and the relevant variables are shown in Fig. 11 where

- P is the ratio of the number of carriers produced to the number of impinging photons, a number near unity for cadmium sulphide.
- φ is the photon flux falling on the photoconductor in photons/second.
- q_e is the magnitude of charge on the electron, 1.6×10^{-19} coulombs.
- τ is the lifetime of the carriers produced, the mean time the carriers are available to conduct before they recombine and disappear.
- μ is the mobility of electrons in the photoconductor.
- a, b are the dimensions of the photoconductor.

The current in the photoconductor is

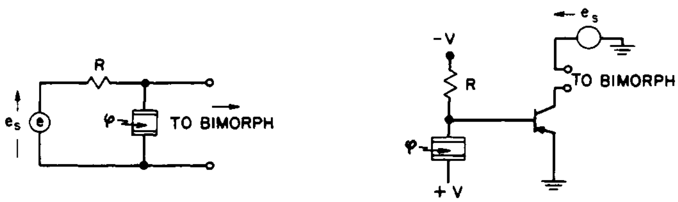


Fig. 9. Two photodetector switch circuits. (a) Resistor-photoconductor circuit. (b) Photoconductor-transistor circuit.

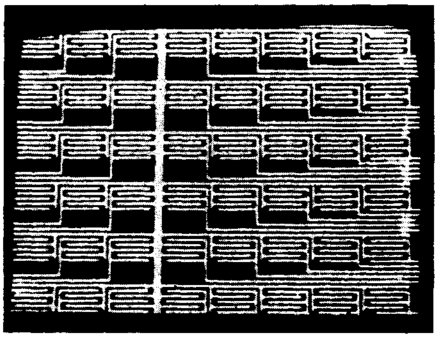


Fig. 10. Photoconductor array.

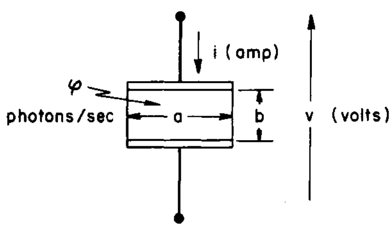


Fig. 11. Dimensions of the photoconductor.

$$i = P\varphi q_e \frac{v\mu\tau}{b^2}. \tag{20}$$

If one used an ordinary p-n photodiode, and if its value of P were the same as the value indicated above for a photoconductor, its terminal current is readily seen to be

$$i = P\varphi q_e, \tag{21}$$

which we shall call the "optical current." For the case under consideration, the optical current is about $3\times 10^{10}\times 1.6\times 10^{-19}$, or roughly 5 nA.

If one uses a phototransistor as the photodetector, the current is found to be, assuming again the same value of P,

$$i = P\varphi q_e\beta \tag{22}$$

where β is the current gain of the phototransistor. The value of β is typically about 100 in newer commercial versions of phototransistors.

Clearly, the phototransistor has advantage over the diode. In comparing the phototransistor and the photoconductor, β must be compared with $v\mu\tau/b^2$. Using $v=1$ volt, $\mu=200$ cm^{2}V^{-1} seconds^{-1}, $\tau=10^{-3}$ seconds, $b=2\times 10^{-2}$ cm, all of which might be applicable to cadmium sulphide, one finds that $v\mu\tau/b^2$ to be 500.

To switch the 10's of μA on and off in the bimorphs with the optical current of 5 nA requires an overall current amplification of about 10^4. This value appears attainable with the combination of a transistor and either a photoconductor or a phototransistor. Convenience of fabrication of the combination appears at this point to be the deciding factor.

III. Reading Tactile Images of Alphabetic Shapes

Computer-Controlled Instrumentation System

The ability of subjects to read vibrating and moving tactile images of alphabetic shapes, corresponding to those that would be produced by the proposed hand-held device described above, has been investigated. For this study, a digital computer simulation of the photocell array was programmed. In this system, the computer controlled an array of tactile stimulators, activating each stimulator in the array as if it were connected to a photodetector gate on which printed material was being imaged. The advantages of using a computer system for this study were that the stimuli could be precisely controlled, experiments could be initiated immediately, and a wide variety of parameters could be easily tried before development of a particular reading aid design was begun.

The computer system used has been described previously by Bliss and Crane [14] and is shown schematically in Fig. 12. In this system, the CDC 8090 computer is used to store the stimulus patterns (alphabetic shapes, in this case) and the sequence in which they are to be presented. Then the computer is programmed to present the alphabetic shapes in their proper sequence according to a particular spatial-temporal mode of pattern presentation. The computer transmits 12-bit words, each word representing one row of the spatial pattern to be displayed, to specially constructed external equipment. This equipment stores up to 96 bits (8 words) and simultaneously activates the specified tactile stimulators. In the experiments reported here, the computer was programmed to move the letters across a 12-by-8 array of tactile stimulators in much the same way as certain electric light news display signs. That is, in each cycle of machine operation, the letters are shifted left by one column. This relative motion simulates moving a hand-held photocell array from left to right across a line of type with perfect tracking.

Over 200 hour-long sessions have been run with this equipment. Some of these were exploratory, in some reading rates were measured, and in some certain display parameters were varied and reading accuracy tested. Figure 13 shows a subject reading with the equipment.

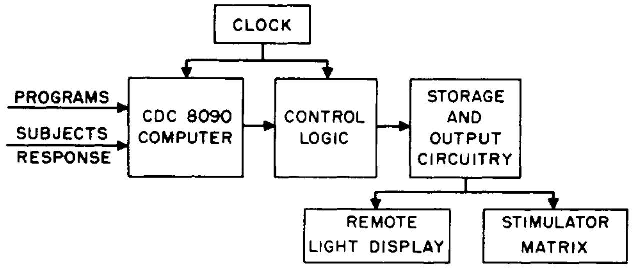


Fig. 12. Block diagram of digital computer-controlled system.

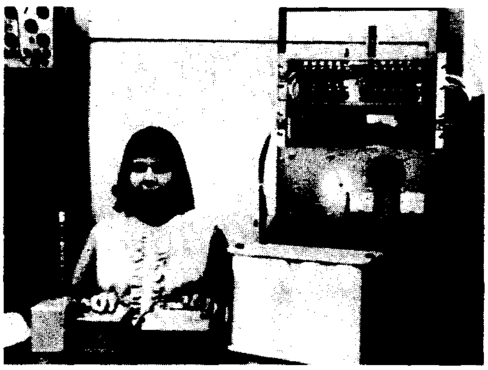


Fig. 13. Subject reading with her left hand from the bimorph array.

Subjects

Three subjects were used in the sessions and they are described briefly below.

Subject 1: Our initial subject was a 12-year-old girl who is in the seventh grade at a regular school. She is an avid Braille reader. With sections from the same article from the *Saturday Evening Post*, she scored 76 wpm on a Braille I reading test and 125 wpm on a Braille II reading test. She has been partially blind since she was about 8 months old and totally blind since she was about two years old.

Subject 2: This subject was a 16-year-old senior in a regular school. He reads Braille every day and can read Braille at about 100 wpm. He went blind gradually and could read and see colors until he was 10 years old. He has had no light perception for three or four years.

Subject 3: This subject was an 18-year-old sophomore at Stanford University. She reads Braille every day and has read as fast as 137 wpm. She was blind from birth and has never had any light perception.

C. Stimulus Conditions

Two types of tactile stimulators were used in the experiments reported here. In a few sessions airjet stimulators were used either for comparison purposes or because the between-stimulator spacing could be more readily varied. The airjets were from 0.031-inch outlet ports and were activated by electromagnets.

As shown in Fig. 8, the piezoelectric reed stimulators consisted of 96 lead zirconate bimorphs cantilevered at 45 degrees from the base so that each can vibrate like a reed. Rounded tips of 25-mil diameter drill rods were epoxyed to the free ends of the bimorphs along a vertical axis. The array of free tips were accurately positioned so that they were flush with a horizontal plane. When the bimorphs are activated, the tips protrude through the perforations in the plate.

Each subject was allowed to adjust the height of the sensing plate and his finger position to his liking. The subjects lightly placed their fingers against the perforated sensory plate. Since the bimorphs were mounted at a 45° angle to the sensing plate, the pin motion was both normal and tangential to the skin surface. Because finger pressure can relatively easily reduce the bimorph vibration, the most intense sensation is felt when the rest position of the skin is slightly above the rest position of the bimorph tips. Under this condition the bimorph tip impacts the skin and contact between the bimorph tip and the skin is broken each cycle of bimorph vibration. However, since the sensory plate is flat and the finger is curved, if this condition is met at the edges of the finger, then the bimorphs in the center are greatly damped and produce less sensation.

In all cases the subjects used only one finger at a time and the fingers they used corresponded to the fingers they used in reading Braille. Figure 14 shows the placement of a finger on the stimulator array. The reading rates were sufficiently great that active finger movements to scan a letter were futile; thus the subject always kept his finger in a stationary position.

The sensation from the bimorph stimulators is described as a very localized vibration, almost a tickle.

Most sessions were conducted with the block letters shown in Fig. 15. A few sessions have been conducted with the alphabetic font shown in Figs. 16 and 17, which was obtained by quantizing standard pica typewriter letters on an 8-by-12 grid.

Reading Rate Determinations

During the sessions in which reading rate determinations were made, a strict schedule of practice, rest, and test periods were followed. These one-hour sessions included four 2-minute tests. Before each test the equipment was set to present the words at a predetermined fixed rate. The subject called out the words as they were recognized and was only corrected in the extreme cases in which a sentence or more was missed. Only correct responses were counted in determining the reading rates.

In Fig. 18, the average performance on the four tests is shown for each session. Note that all three subjects were able to read at a 20 wpm rate after 17 hours of training and that Subject 1 and Subject 2 were able to read at about 30 wpm after 50 hours of training. Subject 3 has only had about 15 hours of training, but her progress so far has been more rapid than that of Subject 1 and Subject 2.

Some of the variability in their reading rate determinations is due to variations in the difficulty of the read-

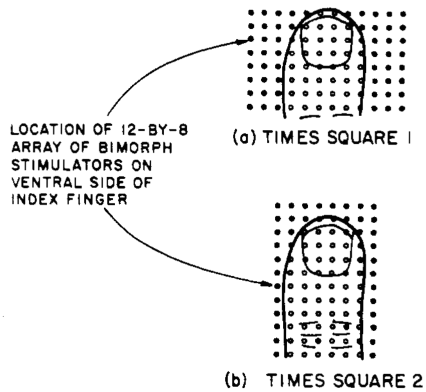


Fig. 14. Location of finger stimulation with the bimorph array.

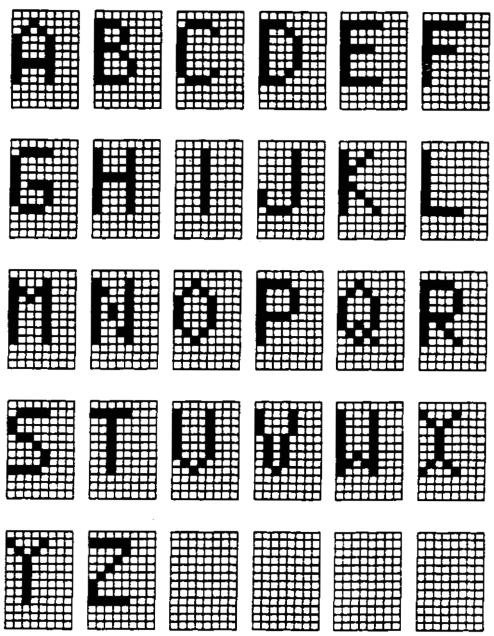


Fig. 15. Block letter alphabet.

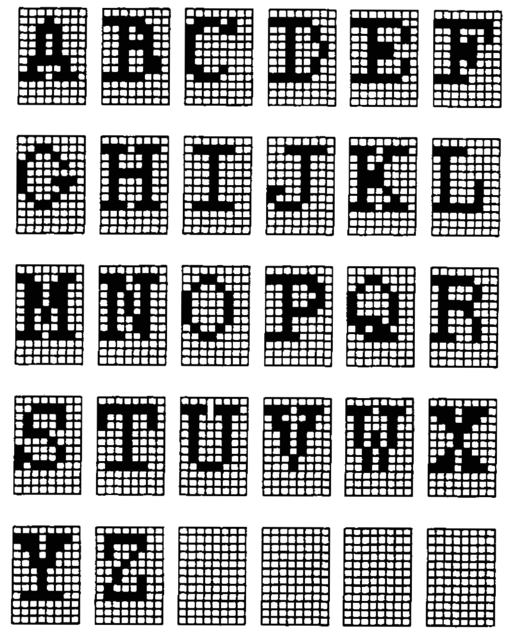


Fig. 16. Quantized pica typewriter upper case letters.

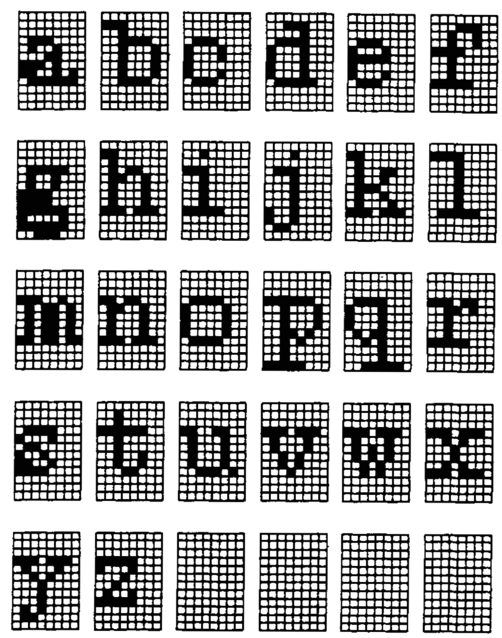


Fig. 17. Quantized pica typewriter lower case letters.

ing material. The textual material used in each session is given in Table I. However, other factors influenced the reading rates to a large extent also. For example, the large dip in the curve for Subject 2 was in part caused by giving him a too high presentation rate (31 wpm) too soon. His accuracy fell to such an extent that his correct word per minute rate was lower than it had been for slower presentation rates.

After session 52 with Subject 1, session 59 with Subject 2, and session 14 with Subject 3, training was begun on the quantized typewriter letters shown in Figs. 16 and 17. These letters required considerable training before each letter could be recognized with facility. The main reasons for this difficulty were that, unlike the block letters, the shapes were initially unfamiliar to the blind subjects and that these letters are obviously less distinguishable tactually than the block letters. However, after about thirteen sessions, each subject could recognize the lower case typewriter letters with about 98 percent accuracy. After these letter familiarization sessions, textual reading was reinstituted, with the results shown in Fig. 18. Thus far the reading rates are below those attained with the block letters, but there is no reason yet to feel that with further practice this will not increase.

The Effect of Array Width

An important question is how many stimulators are necessary for adequate perception of the letters. Since the letters are moving past a fixed "window," two related questions are: 1) How large should the "window"

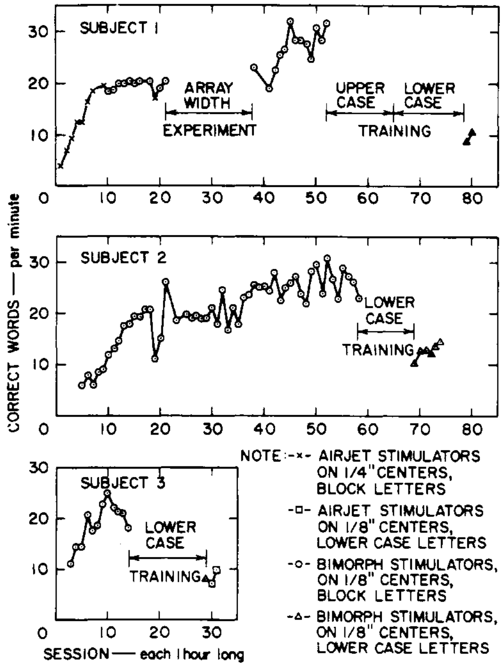


Fig. 18. Textual reading performance curves.

TABLE I

READING MATERIAL

Subject	Source of Material
S_1	1) *New Horizons Through Reading and Literature* (California State Department of Education, Sacramento, California, 1961). 2) Ian Fleming, *Thunderball* (New American Library, New York, 1962). 3) *The Beatle Book* (Lancer Books, Inc., New York, 1964). 4) *The True Story of the Beatles* (Bantam Books, Inc., New York, 1963). 5) *Saturday Evening Post*, June 20, 1964.
S_2, S_3	1) *Saturday Evening Post*, June 20, 1964. 2) A. Huxley, *Brave New World* (Bantam Books, Inc., New York, 1955). 3) John C. Pallister, *The Insect World* (Dept. of Insects and Spiders, The American Museum of Natural History). 4) *Stanford Research Institute Journal*, No. 1, 1964. 5) *Reader's Digest*, July and October, 1964. 6) Jules Romains, *The Death of a Nobody* (New American Library, New York, 1961).

be? 2) How many points within the window are needed for adequate resolution? In an attempt to shed some light on this question, a number of sessions with Subject 1 were devoted to practice and tests with various effective widths of the stimulator array.

Since Subject 1's index finger made contact with only four columns of the array, tests were only run for array widths of 1, 2, 3, and 4 columns. Since the letters used in these sessions were five columns wide, some degree of temporal integration had to be performed by the subject with each of the array widths used, the one-column array requiring the most. Thus all of the reading done during this series of sessions was analogous to a slit

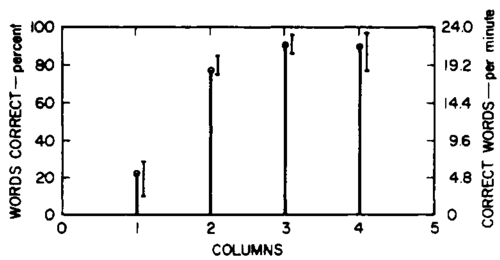


Fig. 19. Reading accuracy vs. window width in columns.

scan of embossed letters, the variable being the width of the slit.

The parameters held constant were a presentation rate of 24 wpm and a stimulator frequency 250 pps. All material was from *The Beatle Book* (see Table I). The array width was held constant during any one session and a schedule of practice and test periods was followed. To minimize learning effects, the order in which the array widths were tested was 4, 3, 2, 1, 1, 2, 3, 4.

Figure 19 is a graph of the performance at each array width. The points on the graph are averages of all tests at each array width and the range of test scores are also indicated. Note that while only 22 percent correct identification was possible with one column, 77 percent correct identification was possible with two columns. This large difference between one and two columns appeared to be due to a better ability to perceive corners in the two-column case.

IV. Discussion

The engineering design considerations and experimental results presented here lead the authors to an opinion and a conclusion: 1) that microelectronics provides new and potent implements for making an opto-electronic-mechanical device to generate tactile images from printed material and 2) that tactile images of printed material are readable. Lead zirconate bimorph reeds are found to be convenient and efficient tactile stimulators which could be combined with photoconductors, via a single transistor switch, in an integrated construction to produce a small, compact, direct-translation reading aid. However, implementation of these techniques into a complete device has not yet been accomplished.

Reading tests, with a computer system controlling an array of bimorph tactile stimulators to simulate the photodetection part of this device, indicate that a tactile image of alphabetic shapes, consisting of a dense array of vibrating pins, is readable. In these tests, three subjects were reading material aimed at these age and education levels at a rate over 20 correct words per minute (24 wpm presentation rate) by the end of 17 hours of training. (Subject 3 attained this rate after only 6 hours of training.) Even though the reading rate determinations with Subject 1 were interrupted for other experiments, she reached a correct-word reading rate above 30 wpm (37 wpm presentation rate) by her 45th session, and Subject 2 reached this rate by his 52nd session. At this point, the ultimate limit of reading capability and the range of usefulness is not clear, but these initial results indicate that further study is warranted.

The fact that material was presented at a constant rate in our sessions undoubtedly had a large effect on the correct word reading performance. As with visual reading, a much better system would be to allow the subject to control the presentation rate continuously. An important problem yet to be studied is what form this control should take, as well as other control capabilities, such as for "browsing" through the material.

The results of our reading tests have some interesting comparisons with related experiments reported in the literature. Geldard [15] reports a reading rate of 34 correct words per minute with one subject after 65 hours of training, with an arbitrary tactile code employing 5 stimulator locations on the chest, 3 intensities, and 3 durations. Our results suggest that alphabetic shapes can be read tactually as rapidly as this arbitrary code with about the same amount of training. The advantage of alphabetic shapes in terms of the resulting complexity of a reading aid is obvious.

Poulton [16] tested visual reading of typescript through a window, varying the speed and size of the window systematically. His results are shown in Fig. 20 with a tactile reading rate from our data superimposed on his curves. These curves imply a model in which reading rate, for any given accuracy, is proportional to the size of the window. Our reading rates indicate a higher accuracy than the extrapolated prediction of his curve for visual reading. However, the agreement between this model, derived from visual reading with window sizes greater than three letter spaces and our tactile reading rates with window sizes less than one letter space is remarkable.

In our experiments on array width, the experimenter could not read the visual display as well as Subject 1 could read the tactile display with one- and two-column widths. While this was an informal observation, it also suggests that the tactile channel may have better temporal integration than vision. However, more training and testing is needed on both visual and tactile reading with small window sizes to verify this hypothesis.

The research on the optophone, reviewed by Freiberger and Murphy [3], permits a comparison with an analogous one-column auditory display. They report a 10 wpm reading rate after 100 hours of training. The large improvement we found in going from one to two columns may account for part of this relatively poor performance. However, the experiments with the optophone involved manual tracking of the material by the subject, which undoubtedly was a factor also.

What, then, is likely to be the reading rate attainable with a tactile direct translation reading aid? To the extent that the relations implied by Fig. 20 are applicable to this situation, one is led to the conclusion that, as long as the field of view is one space or less, the reading rate will be less than 50 correct words per minute. In discussing reading rates, Freiberger and Murphy [3] state:

> ... We feel that most blind people would be quite satisfied to be able to read ink-print at 180 wpm (perhaps comparable to Talking Books and to highly skilled reading of Braille), that many would tolerate 90 wpm (slow public speaking), and that for special reading tasks even speeds of 15 to 20 wpm (slow Morse Code) would be useful. Some subjects were reported to feel they would read for pleasure if they could attain 20 wpm ...

Thus, the rates already demonstrated with a tactile direct translation reading aid appear to be within the range of usefulness.

What are the prospects for increasing the tactile reading rate, still retaining the direct translation approach? When our subjects were encouraged to use two fingers with our Times Square 1 display shown in Fig. 14(a), thus increasing their field of view to an equivalent of two letter spaces, they reported that the patterns were too confusing. Whether this confusion can be overcome with practice, with a corresponding increase in reading rate, remains to be seen.

However, innovations and improvements should be expected in the coming period of development. For example, one approach to increase the possible reading rate is to combine a relatively high-resolution tactile image, with a field of view equal to only one letter space, with adjacent subsidiary displays having a large, but low resolution, field of view. We are presently simulating this "fovea" type display to determine if significantly increased reading speed is possible with this technique.

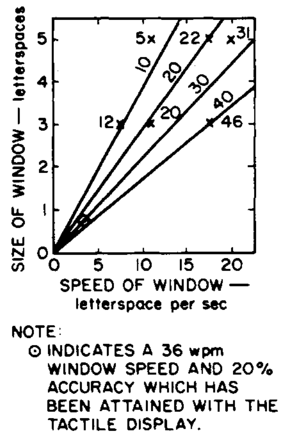


Fig. 20. (From Poulton, [16]) Equal-error contours showing the relationship of speed of reading to size of window for a group of twelve subjects. Each cross marks an experimental condition. The value of the mean error per 100 words for this condition is printed beside the cross. The equally spaced contours have been fitted by eye.

Acknowledgment

The work described here began as separate projects by the two authors working in two laboratories with different sponsors. At Stanford University the first model of a photocell-piezoelectric device was made as an engineer's thesis project under ONR support by G. Alonzo under the supervision of the first author. In the course of its construction University colleagues, particularly Dr. I. Wunderman and L. Parfaite, made many helpful suggestions. The device demonstrated engineering feasibility, but definitive reading tests could not be made with it. Basic experiments on tactual perception had been initiated earlier at the Stanford Research Institute by the second author using airjet stimulators, developed under Contracts NAS 2-912 and NAS 2-1679. These stimulators were controlled by a computer instrumentation system developed under Contracts AF 33(657)-8824 and AF 33(615)-1099. At this point a piezoelectric reed array, compatible with the SRI computer system was constructed at the University by D. Sorenson. All of the tests and evaluations described here were made at SRI under the direction of the second author. The reading tests were conducted by T. Ferrera and B. Lane and significant technical contributions were made by Dr. H. Crane and K. Gardiner.

We appreciate the support, enthusiasm, and interest of colleagues and sponsors in the course of the work reported here.

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In 1956 he joined the Stanford Research Institute, Menlo Park, Calif., where he worked on automatic alphanumeral reading systems. In 1958 he received a National Science Foundation Fellowship for graduate work at M.I.T. At M.I.T. he joined the Sensory Aids Research Group and did his thesis work on "Communication via the Kinesthetic and Tactile Senses." In 1961 he returned to SRI, where he is presently Head of the Bio-Information Systems Program and Project Leader of studies on tactile perception, arthropod vision, and human tracking characteristics. He is Project Supervisor on the development of an electronic mobility aid for the blind. He has an appointment as Lecturer at Stanford University, and has taught courses on biocommunications and pulse and timing circuits.

Dr. Bliss is a member of Phi Eta Sigma, Pi Mu Epsilon, Eta Kappa Nu, Tau Beta Pi, and Sigma Xi. He is also a member of the National Academy of Sciences' National Research Council Subcommittee on Sensory Aids.

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After aiding in the development of the VT proximity fuse at the Carnegie Institute, Washington, D. C., during 1941, he joined the General Electric Research Laboratory in 1942. At General Electric he has performed extensive research on electrometer tubes, millimeter-wave reflex oscillators, electron accelerator guns, color television picture tubes, gas discharge tubes, and ultrahigh vacuum pressure gauges. He also developed the lanthanum boride cathode used in various electron tube devices. In 1955 he became Manager of what is now the Plasma and Vacuum Physics Branch of the General Physics Laboratory at the General Electric Research and Development Center, Schenectady, N. Y. This group was responsible for a major research effort leading to the development of the high-power vacuum switch.

Dr. Lafferty is a Fellow of the American Physical Society, Secretary of the American Vacuum Society, and an associate editor of *The Journal of Vacuum Science and Technology*.

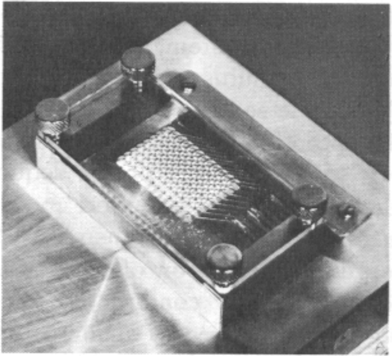

Fig. 8. A 12×8 array of piezoelectric bimorph tactile stimulators.

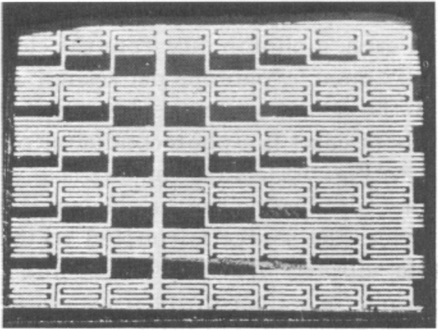

Fig. 10. Photoconductor array.

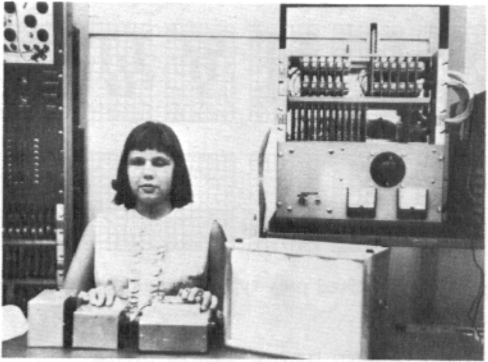

Fig. 13. Subject reading with her left hand from the bimorph array.